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AN INVESTIGATION OF THE PREVENTION OF ICE ON

THE AIRPLANE WINDSHIELD

By Lewis A. Rodert

SUMMARY

An investigation has been completed on several methods for the prevention and removal of ice on an airplane windshield. Tests were made on the use of electric heating, hot-air heating, and an alcohol-dispensing, rotating wiper blade.

The results showed that vision through the airplane windshield could be maintained during severe icing conditions by the use of heat. When put in operation prior to the formation of ice on the windshield, the rotating wiper blade prevented the formation of ice. A combination system that employs the use of heated air and a rotating wiper blade would appear to give protection against formation of ice on the windshield exterior, prevent frost on the interior, and provide for the removal of rainfall.

INTRODUCTION

The National Advisory Committee for Aeronautics is conducting a program of ice research aimed to reduce the risks now attendant with airplane operations during icing conditions. A part of this program is concerned with the prevention of ice on the airplane windshield, which is known to be a problem in urgent need of solution. An investigation has been completed on the windshield icing problem in which several possible solutions were tried. The methods tested in the present investigation involve the application of (1) heat from an electric source, (2) heat from the engine exhaust, and (3) an alcohol-dispensing rotating wiper blade. Inasmuch as the problem of ice prevention exists in several forms, it is anticipated that several different methods may find application in some manner or location on the airplane. The obstructions of vision through a windshield may result from ice or snow formations on the exterior surface or from the formation of frost on the inside. The object of the present investigation, therefore, was to determine the extent to which the several methods could preserve vision. Observations were also made to determine the capacity of the rotating wiper blade to remove falling rain from the airplane windshield.

APPARATUS

Most of the tests on the models applying to various methods included in the investigation were made under simulated icing conditions in flight although some preliminary tests of the electrically heated model were made in the N.A.C.A. 7- by 3-foot ice tunnel.

The temperatures necessary for icing conditions were obtained in flight by climbing to the proper altitude. During the tunnel tests, the air temperature was controlled by a refrigeration system. Icing conditions were simulated during all the tests by establishing the necessary temperatures and discharging waterdrops into the air stream ahead of the models. The waterdrop size, and therefore the type of ice, was controlled by the relation existent between the air and the water pressures leading to the spray nozzles. In the determination of the capacity of the rotating wiper blades to remove falling rain, simulation of the natural condition of rainfall was also produced by the use of the spray nozzles.

Electrically Heated Tunnel Model

The tunnel model of the electrically heated windshield was mounted in the leading edge of an airfoil shape as shown in figure 1. The dimensions of the transparent area of this model are 9 inches by 9 inches. The test panel is made of two panes of glass $1/8$ inch thick, mounted in a frame and separated by a $1/4$ -inch gap. The gap between the two panes of glass contains electric heating wires. A liquid dielectric, ethylene glycol, was used to surround the heating wires and aid the transmission of heat from the wires to the glass and prevent local overheating of the glass panes. Details in the construction of the panel rim provide for the electrical connections, the filling of the interior space with ethylene glycol, and its retention, and a space into which the heated ethylene glycol could expand. The power consumed by the heating wires was measured by the voltammeter method. The power was controlled by regulating the voltage across the heater with a rheostat.

Electrically Heated Flight Model

The flight model of the electrically heated windshield

was mounted in the right front windshield frame of a four-place cabin monoplane (fig. 2). The dimensions of the transparent region of this panel were 5 by 9.75 inches. A photograph of the model prior to installation in the airplane is shown in figure 3(a). The outside dimensions of the frame, which was set into a cut-out in the regular windshield, were 8.1 by 13.1 inches. In addition to the heating-element wires contained between the panes of glass, a heating wire was enclosed within the rim of the panel. In other construction details, the flight test model was similar to the one tested in the tunnel.

A section drawing of the flight-test model is shown in figure 3(b). The wiring diagram is shown in figure 3(c). Eight horizontal heating wires were spaced 0.56 inch. The power consumed was measured by electric meters in a manner similar to the measurements made during tunnel tests. The power consumed was controlled by rheostats in the panel and the rim-heater circuits. The power for the test panel was supplied by two 12-volt batteries connected in parallel.

Air-Heated Flight Model

The heated-air windshield mounted on the airplane for flight tests is shown in figure 4. The test panel, when mounted as shown, was set into the side window of the cabin airplane at an angle of 30° with the side of the craft. This model was also mounted in a cut-out in the right front windshield during part of the tests. When mounted in the front windshield panel, the direction of the hot-air flow in the model with relation to the direction of the air stream over the outside was thought to be unfavorable to the most efficient operation of the heating system. In order to avoid the extensive changes required to both the airplane windshield frame and to the model to obtain a desirable orientation, the model was moved to the side location. The side mounting was therefore utilized for the rest of the tests because it eliminated the objectionable features of a mounting in the front panel of this particular airplane and yet provided conditions that would give valid test results. The dimensions of the exterior of the frame were 9 by 14 inches. The size of the transparent region over which ice was prevented was 6 by 11 inches. Some glass breakage was experienced during the early tests with this model owing to improper mounting of the glass. When the glass panes were uniformly heated and were insulated from vibration or physical deflection, breakage did not occur.

The important details of the construction are shown in figure 5. The test model consisted of an intake duct, regulating check and by-pass valves, frame, and two panes of glass. The glass panes were mounted in a frame and separated by a small air gap. Safety glass and double-strength window glass were used with equal success in the model. The structure of the frame provided for a variation of the gap between the panes of glass from $3/16$ inch to $1/8$ inch. The gap between the panes of glass and the edges of the frame provided a duct through which heated air from the cabin air heater was passed.

The temperature drop of the air passing between the glass panes was measured by thermocouples located in the heater and in the air outlet (fig. 5). The velocity of the air through the model was measured by pitot and static tubes located in the duct at the air outlet.

Rotating Windshield Wipers Tested in Flight

Tests were made on the rotating wiper blades in flight with the models mounted as shown in figures 6, 7, and 8. Three different drives for the blades were provided during the investigation. An electric-motor drive developed at the N.A.C.A. was used during all the ice-prevention tests. The motor of this drive consumed 50 watts of electric power when connected to a 12-volt battery. The speed-control range of this model varied from 300 to 750 r.p.m. The windshield-wiper blade shaft was driven by the electric motor through a flexible shaft. Another drive was developed at the N.A.C.A. in which the windshield-wiper blades were driven through a flexible shaft by the airplane engine. The flexible shaft was attached to the auxiliary tachometer-shaft connection.

A commercially developed model of the electric-motor type of drive was tested for the removal of rain during the investigation. The electric motor in this drive consumed 90 watts of electric power from a 12-volt battery. The drive permitted the wiper blade to be turned at speeds up to about 2,100 r.p.m. The blade shaft was driven by the motor through a flexible shaft in a manner similar to the model developed at the N.A.C.A. The installation of this model is shown in figure 8.

The wiper blades tested with the various drives are shown in figure 9. Each wiper blade covered a disk on the

windshield 10 inches in diameter. Sections 9(a), 9(b), and 9(c) were developed at the N.A.C.A. laboratory. The wicks indicated in the figures were of wood felt. The wiper blades were constructed of 1/32-inch laminated rubber sheets. Sections (d) and (e) are adaptations of automobile windshield-wiper blades. Section (e) differs from section (d) only in that a shield is attached to the leading edge to aid in keeping the blade in contact with the glass when turning at high rotational speeds. Section (f), which has a solid rubber blade, has been developed commercially for use on airplane windshields. Sections (a), (b), (c), and (f) have rigid frames running the full length of the blade diameter. Sections (e) and (d) are made of two 5-inch blades running from the hub outward. The blade sections are held in contact with the windshield glass by adjustable leaf springs mounted upon the blade hub center. Each of the rotating wiper blade shaft mountings provides for the discharge of a fluid, such as alcohol, from the center of the blade shaft upon the outside of the windshield. Isopropyl alcohol, 180 proof ethyl alcohol, and 180 proof ethyl alcohol with a denaturant were used on the wiper blade models during the tests.

TESTS AND RESULTS

Electrically Heated Tunnel Model

The results obtained in the ice tunnel from tests of the electrically heated windshield model are given in table I. The power required to prevent the formation of ice was measured when the test panel was heated prior to discharging waterdrops from the spray nozzles. The model is shown in figure 10(a) after such a test had been made. Attempts to remove ice that had been formed before heat was applied were also made. When ice was allowed to form prior to heating the panel, removal was only partly effected, as is shown in figure 10(b). In this test the ice in direct contact with the glass was melted. The attachment of the ice covering the heated area to that on bordering regions prevented the complete removal of the formation. The bridging of ice over from the unprotected parts of the model apparently prevented the ice from coming in contact with the glass and therefore from being melted. The tunnel model failed structurally when a leak developed and permitted the ethylene glycol contained between the two panes of glass to escape. With no liquid surrounding the

heating wires, the temperature rise of the glass near them caused the glass panels to break. Following the structural failure of the tunnel model, the tests were continued in flight on an improved test panel.

Electrically Heated Flight Test Model

The results of the flight tests with the electrically heated model are given in table II. Figures 11(a) and 11(b) show the flight model after tests during which the formation of ice over the protected panel was prohibited. The tendency of ice to overhang the protected region, which had been experienced during the tunnel tests, was prevented by heating the rim of the protected area. The protrusion of the rim of the test panel about 1/16 inch from the surrounding windshield may also have aided in the prevention of ice from the unprotected areas. The rim heating, which was effective in preventing ice from overhanging the protected panel, required about 2 watts per inch of rim. During the icing tests, visibility through the test section was poor owing to the presence of waterdrops on the exterior surface. The observations made indicated that the visibility during icing conditions, when the model was being heated, was about the same as through an ordinary windshield struck by falling rain. Vision through the double-glass panes and through the ethylene-glycol filler was satisfactory, being about the same as through a similar thickness of plain glass.

Air-Heated Flight Model

The data and observations taken during the test with the air-heated model are recorded in table III. Tests were made during which ice was prevented from forming and in which a thin sheet of preformed ice was removed. Under icing conditions similar to those existent during the tests on the other models, the air-heated panel gave satisfactory protection against the loss of vision. Although the use of the different gap sizes between the various panes of glass slightly changed the temperature distribution along the panel, the degree of ice protection was unaffected by this change. One flight was made to determine the manner and the temperature at which the model would fail to prevent ice. The temperature of the air was gradually reduced and the quantity of water discharged was increased to the largest capacity that could be delivered to the spray nozzle.

These conditions resulted in the formation of ice on the surrounding parts of the airplane windshield at the rate of about 1 inch in 3 minutes. After 20 minutes of flight with an air temperature of 8° F., about 75 percent of the area of the windshield remained clear. Ice was observed to form along the edges of the panel near the air-outlet end. The combination of air temperature and quantity of water used in this test is believed to represent an icing condition more severe than will normally be encountered by aircraft in flight. Unfortunately, photographic results of this test model are unavailable. High surface-air temperatures at the airport when the tests were made prevented the return of the airplane to the hangar with the unmelted ice.

Rotating Windshield-Wiper Blades

Ice was prevented from forming by the rotating windshield-wiper blades but could not be removed if formation occurred before the blade was put in operation. Photographs showing the test panel after a flight during which ice was prevented from forming are shown in figures 12(a) and 12(b). All the alcohols used were satisfactory for the prevention of ice, although the denatured alcohol caused a slight blurring of vision through the protected disk. No data are available regarding the contents of the denaturant used. Later tests were made with pure ethyl alcohol and with isopropyl alcohol. The quantity of alcohol used is thought to be correct. One gallon was sufficient for a flight of 2 hours in moderately severe icing conditions. When ice was permitted to form prior to the rotation of the wiper blade shaft, ice could not be removed. Attempts to operate the rotating wiper blade after ice had formed on the glass resulted in mechanical failure of the drive.

The design of the blade was controlled by the problem of removing rainfall rather than the prevention of ice. All the blades tested gave satisfactory ice prevention although only sections (a), (b), and (f) (see fig. 9) gave satisfactory removal of heavy rainfall. Sections (d) and (e), although requiring less power than did the other model sections, were unsatisfactory because they were lifted off the glass by the air stream over a part of the swept area.

Ice was prevented on the windshield by shaft rotational speeds between 300 and 2,000 r.p.m. The removal of

heavy rainfall required shaft rotational speeds in excess of 750 r.p.m. The 90-watt electric motor with which the commercially developed model was equipped seemed to be the minimum power with which a 10-inch-diameter blade could be driven.

DISCUSSION

The investigation of the prevention of ice on airplane windshields indicates that ice can be both prevented and removed by the use of electrically produced heat or heated air and may be prevented from forming by the use of a rotating wiper blade that dispenses alcohol from its center.

The electrically heated windshield will give its best operation when put in action before ice has formed on the glass. The power required at any air speed for the prevention of ice on the glass by the use of heated wires is given by the equation

$$P_W = 7 \times V^{0.78} \text{ watts per square foot} \quad (1)$$

in which V is the velocity of the airplane in miles per hour.

About 2 watts of the power indicated by equation (1) for each inch of rim of the protected panel should be concentrated in the frame to prevent ice from overhanging the edges. If the heated panel protrudes from the surrounding structure, the tendency of the ice to build out over the protected panel from the edges appears to be reduced. On the basis of observations made during the tests and an analysis of the theoretical design of an electrically heated windshield, it is suggested that the heating wires be arranged perpendicular to the direction of the air stream. On the same basis, it is suggested that the wires be made more closely spaced near the air-stream entering edge of the model than over the rest of the panel. The heating method has been shown to prevent ice on the exterior and frost on the interior of the airplane windshield, but the method makes no provision for the removal of rainfall.

The heat required to prevent the formation of ice by the use of heated air is given by the equation

$$P_A = 24 \times V^{0.78} \text{ B.t.u. per square foot per hour} \quad (2)$$

which gives the same results but in different units than equation (1).

Although the size of the gap between the two panes of glass enters into the theoretical design of the air-heated windshield, the variations made during the tests between 1/8-inch and 3/16-inch were insufficient to effect the prevention of ice. Observations made during the test indicated the desirability of designing the air-heated windshield in such a manner that the flow of air between the panes of glass was in the same direction as the air passing over the exterior. A theoretical consideration of the design also supports this observation. It may also be of interest to note that, according to the theoretical analysis of the design, the power in heat required to prevent ice will be less when laminar flow over the windshield prevails than when the flow is turbulent. Inasmuch as the flight tests were conducted in the propeller wash and turbulent regions, equations (1) and (2) are probably conservative.

The use of the rotating wiper blade dispensing alcohol provides for the removal of rainfall as well as the prevention of ice and therefore may be preferable on some airplane installations to the other methods. The advantage of the rotating wiper blade seems to be that it is easily designed and easily adapted to existing aircraft. The wiper-blade method is, however, restricted because of its inability either to remove a preformed ice sheet over the outside of the windshield or to remove frost from the inside of the windshield. It is thought that provision for manual operation, such as by a handwheel, would overcome this objection. Although the engine-driven wiper had such a provision, no observations have as yet been made on its operation. The method is further disqualified by the limitations in the area that can be covered by a rotating wiper blade and by a partial obstruction of the pilot's vision due to the location of the blade hub.

The heated-air panel appears to be the most satisfactory solution to the windshield-icing problem, provided that a source of air at a temperature of between 170° and 200° F. is available. The air-heated panel has two advantages over the electrically heated panel; it is more easily designed and uses normally wasted exhaust-gas energy; whereas, the electrically heated panel must be kept liquid-tight and must use electric batteries for power. The air-heated model also has the same advantages over the wind-

shield wiper with regard to the source of heat and, in addition, has the advantage of being free from moving mechanical parts. Inasmuch as each of the systems tested has given, in some measure, satisfactory results, it is expected that all will find application according to the requirements and limitations of the particular installation. The possibility and advantages of combining the rotating wiper blade with the hot-air system will be noted. By such a combination, protection against ice will have been doubly provided over a limited area. In addition, the interior of the heated windshield will be protected against frost and provision will have been made for some vision through the windshield when flying in rain. The existing practice of making the airplane windshield retractable or removable by the pilot may become unnecessary if adequate protection against loss of vision due to rain or ice can be provided. The possibility is therefore noted that the added design complications resulting from the installation of ice-prevention equipment may in part be offset by other design simplifications.

CONCLUSIONS

Tests in the 7- by 3-foot ice tunnel and in flight indicated that:

1. Ice could be prevented from forming on the windshield by electric heat, by heated air, or by an alcohol-dispensing, rotating wiper blade.

2. Preformed ice could be removed from the airplane windshield by the use of either electric or hot-air heating.

3. The power required by a heating system for the protection against ice could be computed by one of the following equations:

$$P_W = 7 \times V^{0.78} \text{ watts per square foot}$$

$$P_A = 24 \times V^{0.78} \text{ B.t.u. per square foot per hour}$$

where P_W is the power required by heated wires; P_A , the power required by heated air; and V , the air speed in miles per hour.

4. Approximately one-half gallon of alcohol per hour was required for the prevention of ice over a disk 10 inches in diameter covered by a rotating wiper blade during moderately severe icing conditions at air speeds up to 150 miles per hour.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 16, 1939.

TABLE I. Results of Tunnel Tests of Removal and Prevention of Ice on Windshield by Electrical Heating

(Heated area, 10 by 10 inches; transparent area, 9 by 9 inches)

Type of test	Air speed, m.p.h.	Air temperature, °F.	Power required, watts/sq. in.	Comments
Prevention	80	23	1.25	Ice prevented (see fig. 10(a)), formations at edge of test panel 1-1/4 inches thick. Vision clear. Ice showed some tendency to build out and over panel at the entering edge.
Removal	80	23	1.60	Ice removed from about 20 percent of panel in 15 minutes. (See fig. 10(b).) Ice melted beneath formation but weblike crust not removed except at top of panel.
Removal	80	25	1.89	Ice removed from 30 percent after 10 minutes. Loss of ethylene glycol due to leakage, 60 percent. No ice removed over that section not containing ethylene glycol. Tests discontinued due to failure of model.

TABLE II. Results of Flight Tests of Removal and Prevention of Ice on Windshield by Electric Heating

(Heated area of pane (transparent), 5 by 9.75 inches; total heated area, 8.1 by 13.1 inches; cabin temperature 40° F.)

Type of test	Air speed, m.p.h.	Air temperature, °F.	Power required		Altitude ft.	Comments
			Pane, watts per sq.in.	Rim, watts		
Prevention	95	26	1.43	63	12,000	Ice prevented over 100 percent of test panel in continuous operation, also small preformed formations were removed. Visibility clear. ¹
Removal	90	25	1.43	63	12,700	After 11 minutes, ice melted free from pane and was blown away from 80 percent of the test panel. The lower edge remained covered due to insufficient power in lower rim heater. Slight blurring between wires of test panel. Visibility poor.
Removal	98	25	.55	250	14,800	After 8 minutes, ice formation over panel melted free and moved sidewise until contact was made with ice over adjacent area. Rim power greater than needed.
Prevention	120	26	1.43	63	12,000	Ice prevented over 100 percent of test panel. ¹

¹ The ice-forming conditions did not require a rim heater except at the leading edge. Ice was removed from the unprotected areas along the sides and at the top of the heated panel, indicating that the rim heaters along those edges were not required.

TABLE III. Data from Tests on Windshield Panel When Heated by Cabin Air Heater

(Transparent area, 6 by 11 inches; total area heated, 9 by 14 inches; approximate cabin air temperature, 60° F.)

Ambient air		Panel heating air			Space be- tween panes (in.)	B.t.u. (sq.ft.hr.)	Remarks
Velocity (m.p.h.)	Temper- ature (°F.)	Velocity (f.p.s.)	Temperature In (°F.) Out (°F.)				
^a 106	27	47	172	137	3/16	800	Ice pre- vented and removed
^a 114	27	67	180	148	3/16	1,000	Do.
^b 91	30	67	168	147	1/8	430	Do.
^b 92	31	49	165	153	3/16	280	Dry air
^b 92	31	49	160	147	3/16	320	Ice pre- vented and re- moved
^b 119	8	--	170	--	3/16	--	Ice pre- vented over 80 percent of area

^aRuns made with panel in front windshield.

^bRuns made with panel in frame on the side of the fuselage.

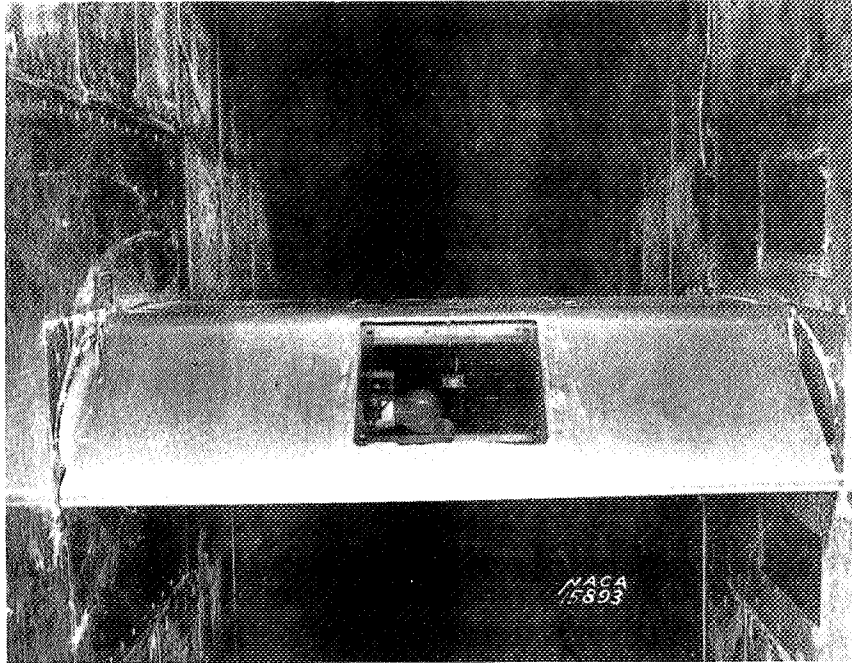


Figure 1.-- Electrically heated windshield model mounted in N.A.C.A. ice tunnel.

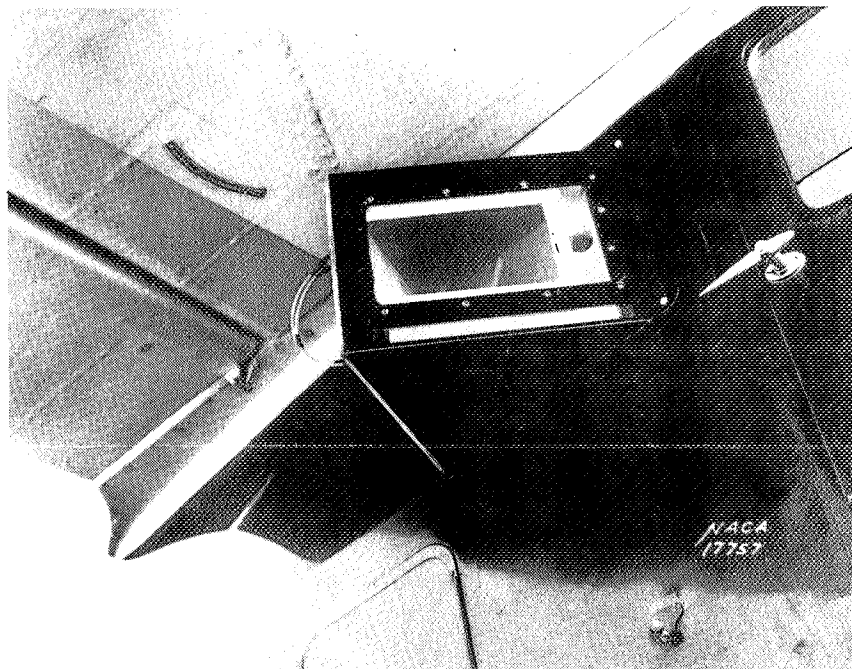


Figure 4.-- Heated-air windshield model mounted in a frame at the side of the airplane fuselage.

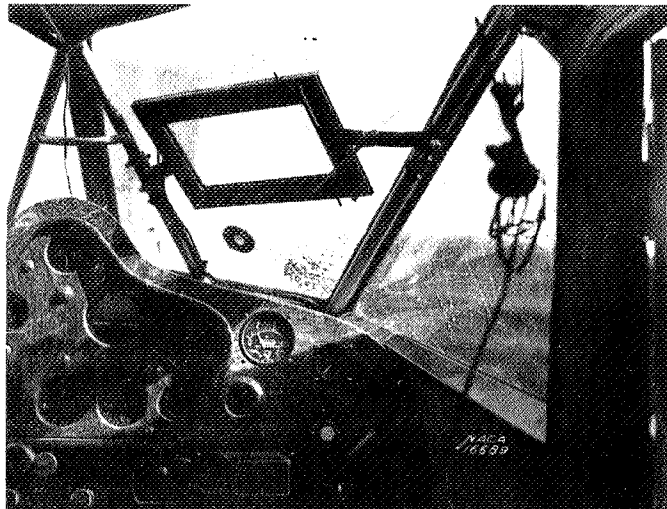


Figure 2.- Electrically heated windshield model mounted in an airplane windshield for flight tests. The main windshield is cut out to permit the insertion of the heated panel.

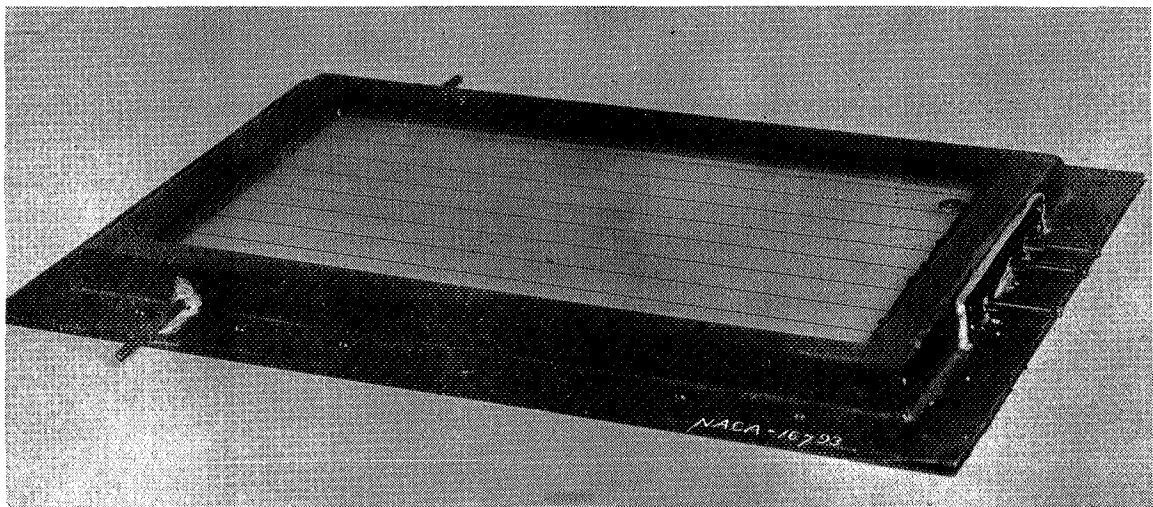


Figure 3a.- Photograph of model.

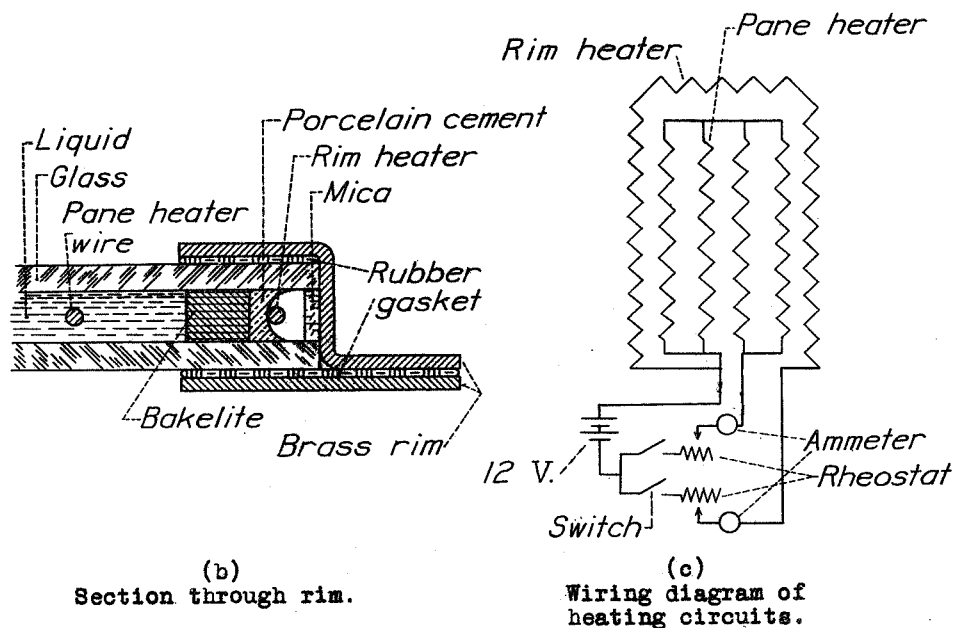


Figure 3b,c.- The electrically heated flight-test model.

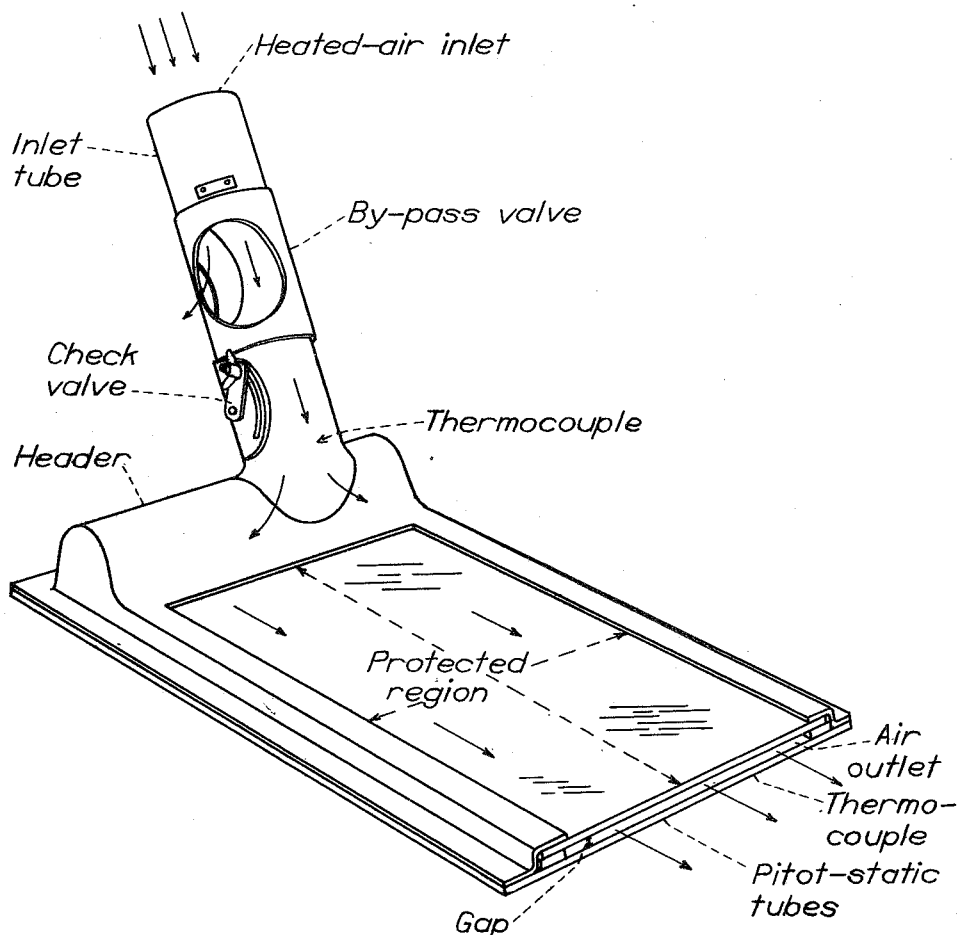


Figure 5.- The heated-air flight-test model.

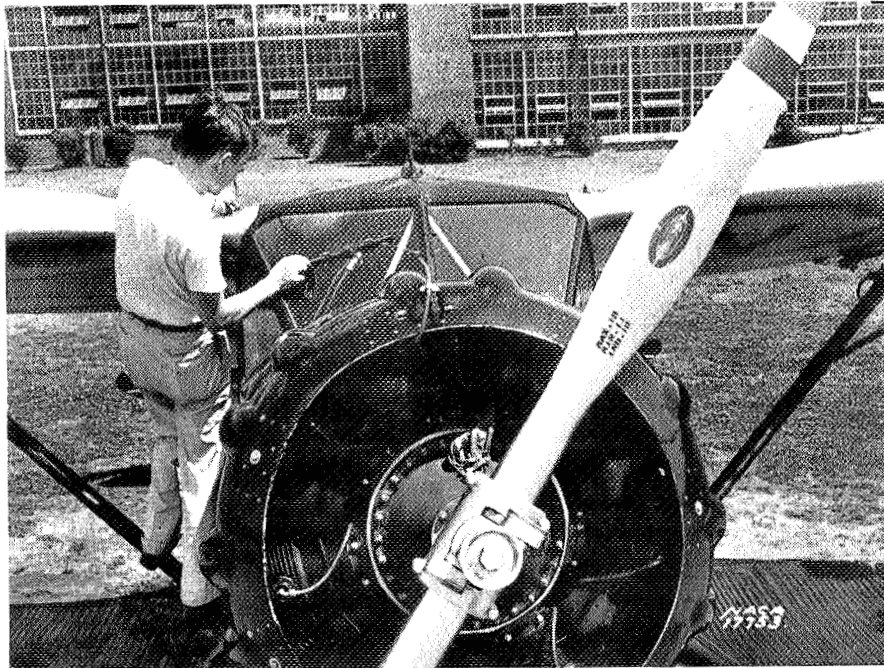


Figure 6.- Rotating wiper blade mounted in the windshield of a four-place cabin monoplane.

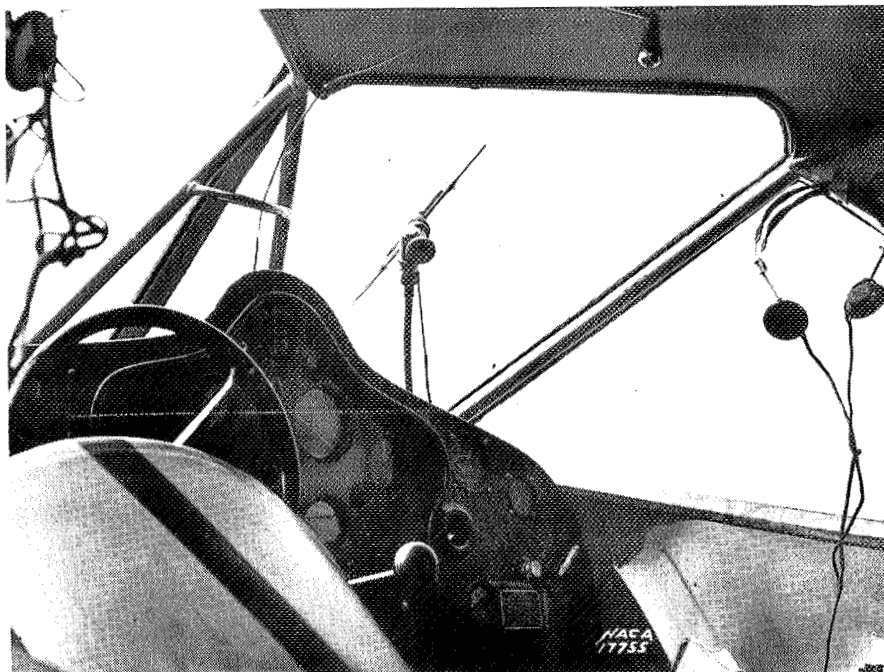


Figure 7.- An engine-driven rotating wiper blade, viewed from the interior of the airplane.

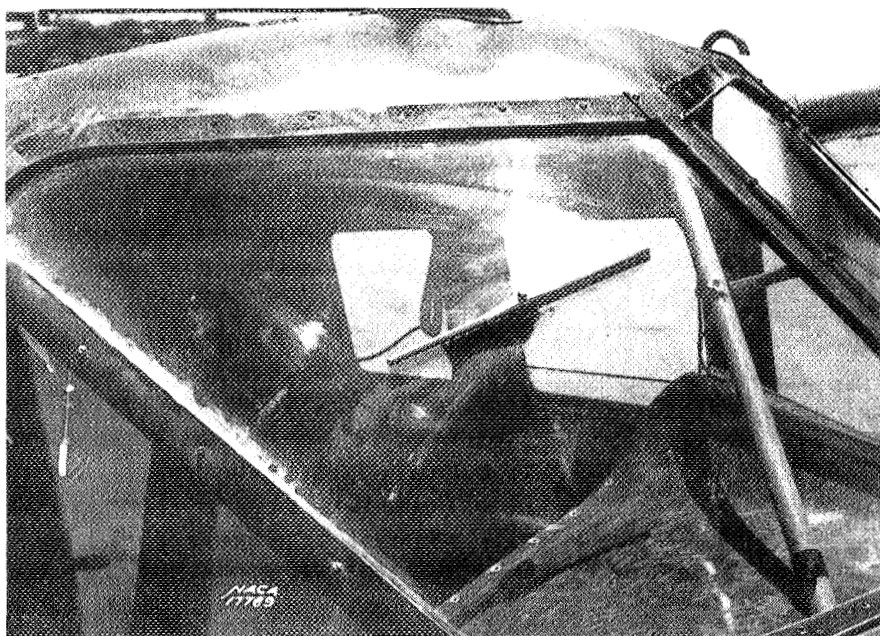


Figure 8a.

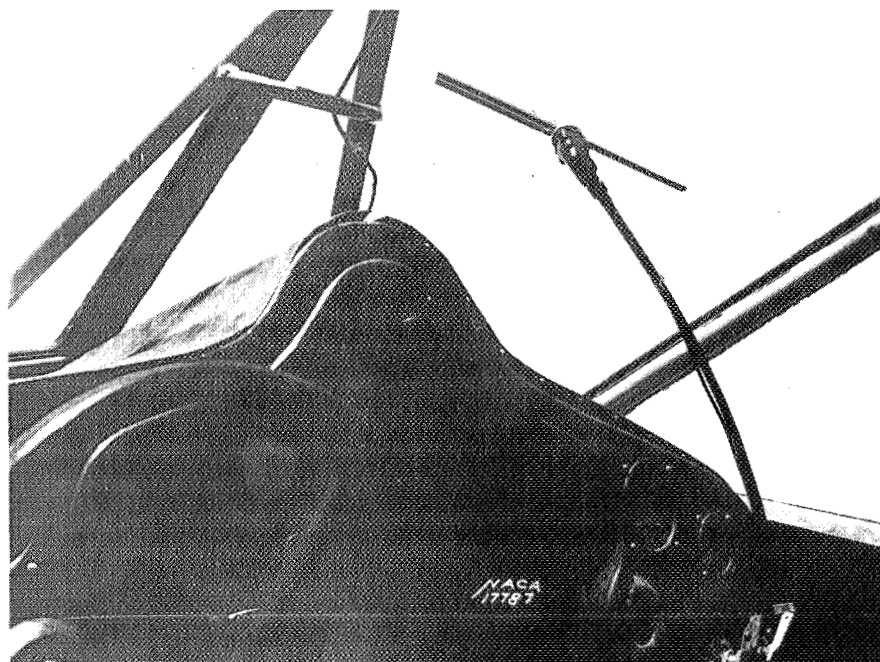


Figure 8b.

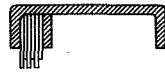
- (a) View from the front of the airplane.
- (b) View from interior of the airplane showing gear and shaft housing and, for a short distance along the shaft housing, a part of the alcohol tube.

Figure 8.-- A commercial model of the electric motor-driven rotating wiper blade.

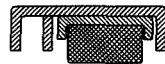
Direction of motion
→



(a) N.A.C.A. wiper blade and wick.



(b) N.A.C.A. wiper blade only.



(c) N.A.C.A. wick only.



(d) Plain automobile wiper blade
(blade in two sections).

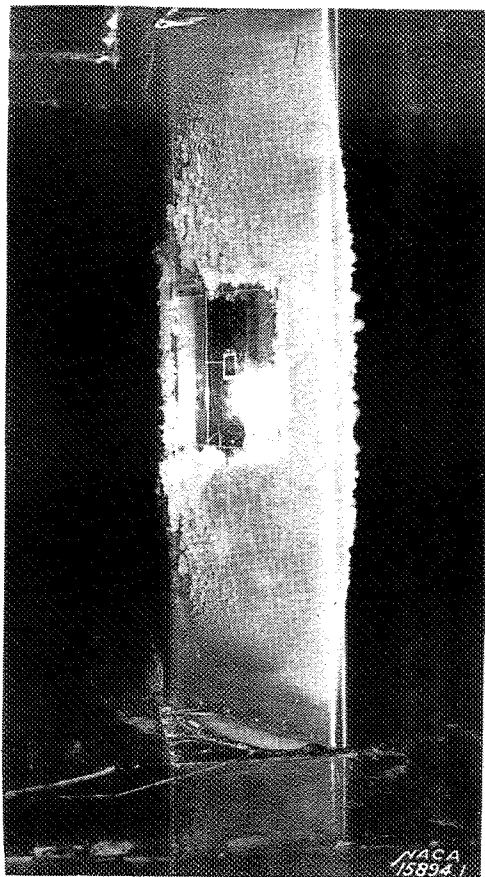


(e) Automobile wiper blade with
deflector (blade in two sections).

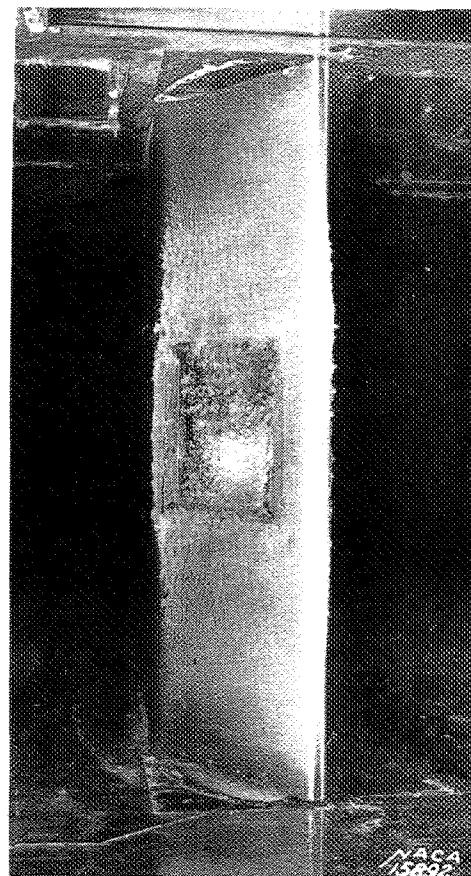


(f) Commercial design of airplane
wiper blade.

Figure 9.- Section views of the blades used in ice-prevention and rain-removal investigations on the rotating-wiper-blade models.



(a) The model after an ice-prevention test.



(b) The model after an ice-removal test.

Figure 10.- Tunnel tests on an electrically heated windshield test panel.



Figure 11a.

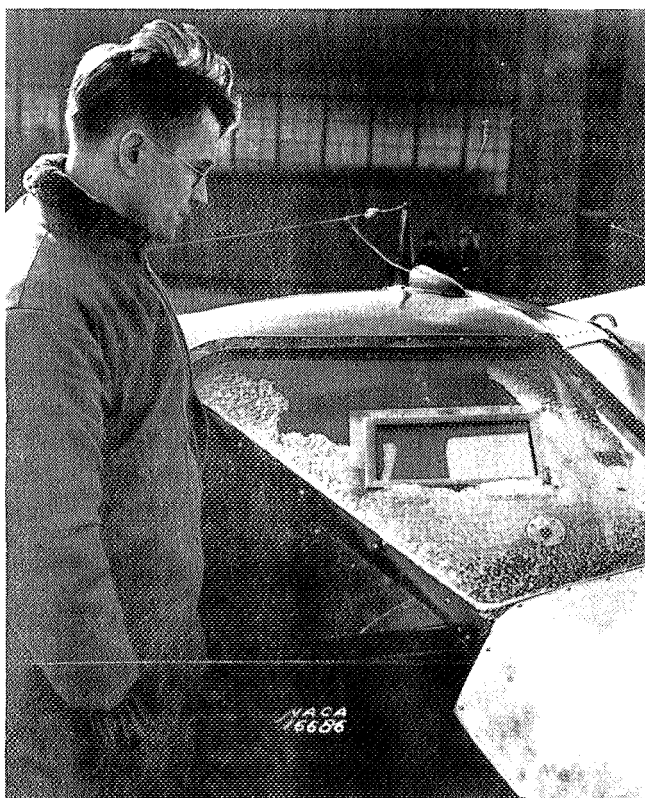


Figure 11b.

(a) Note freedom from overhanging ice at the edges.

(b) A large part of the ice on the unprotected region was blown away during the descent of the airplane.

Figure 11.- The electrically heated flight test model after flights during which ice was both prevented and removed on the test panel.

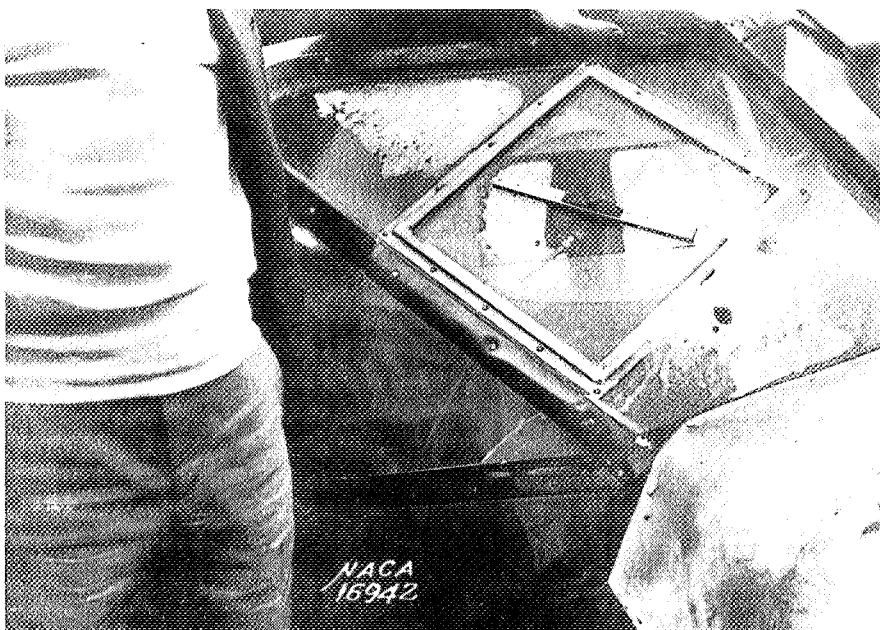


Figure 12a.

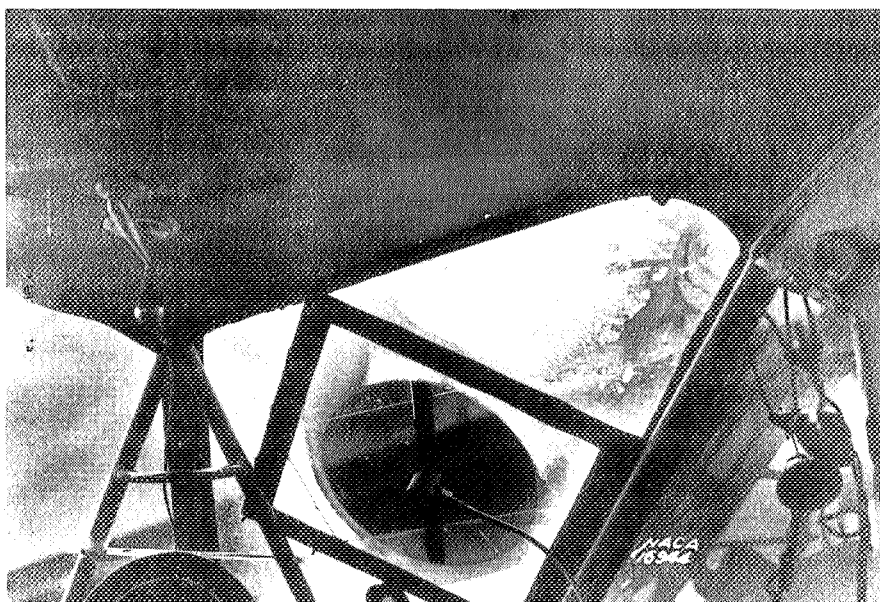


Figure 12b.

- (a) View of the blade from in front of the airplane. Alcohol was discharged from the center of the blade onto the glass.
- (b) View of the gear and shaft housing from the interior of the airplane. Alcohol was fed to the center of the blade through the gear and shaft housing.

Figure 12.- Electric motor-driven rotating wiper blade developed at the N.A.C.A.